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THERMAL DIFFUSIVITY AND LINEAR THERMAL EXPANSION OF STRIPA CORE ROCKS MEASURED IN THE UNCONSTRAINED CONDITION

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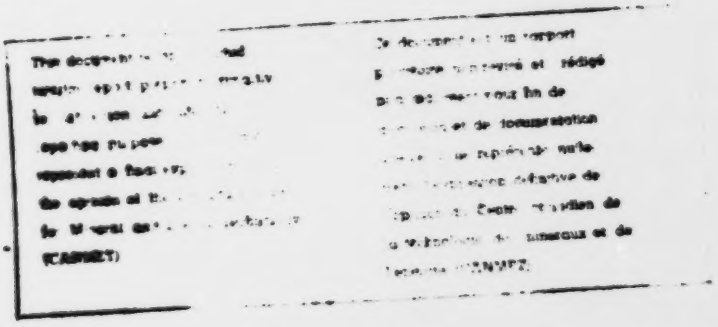

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MICROMEDIA

THERMAL DIFFUSIVITY AND LINEAR THERMAL EXPANSION OF STRIPA CORE ROCKS MEASURED IN THE UNCONSTRAINED CONDITION

by

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ABSTRACT

Thermal diffusivity and thermal expansion of rock specimens from four drill cores of Stripa granite obtained at the Stripa mine in Sweden were measured in unrestrained conditions in the 25° to 500°C temperature range. The thermal diffusivities of these rocks are high at room temperature, however, they decrease rapidly with increasing temperature. The thermal expansion is relatively high and there is a possibility that an internal expansion occurs during the first 50°C temperature rise. The rocks have been estimated to have a low thermomechanical stability.

LA DIFFUSIVITÉ THERMIQUE ET LA DILATATION THERMIQUE LINÉAIRE DE CAROTTES DE ROCHE STRIPA MESURÉES EN L'ABSENCE DE CONTRAINTES

par

V.V. Mirkovich

RÉSUMÉ

La diffusivité thermique et la dilatation thermique d'échantillons tirés des autres carottes de granite Stripa provenant de la mine Stripa en Suède ont été mesurées pour la gamme de températures de 25°C à 500°C en l'absence de contraintes. Les diffusivités thermiques de ces roches sont élevées à la température ambiante, mais décroissent rapidement quand la température s'accroît. La dilatation thermique est assez élevée et il est possible qu'une dilatation interne se produise pendant la première tranche de 50°C d'élévation de la température. Il a été estimé que la stabilité thermomécanique de ces roches est faible.

INTRODUCTION

Radioactive decay of irradiated fuel and the accompanying heat generation may continue for centuries. This heat could have a significant effect on the stability of the surrounding rock mass in an underground nuclear waste repository. The thermophysical properties are the principal parameters for assessing the thermal stability of a rock mass exposed to transient and steady state heat flow. To predict the changes in the thermal gradients with time and temperature, thermal diffusivity of the rocks must be determined as a function of temperature. Furthermore, the rate of thermal spalling of a rock, which in turn may serve as an indicator of its thermal stability, can be estimated from the values of thermal diffusivity and thermal expansion of that rock.

This study was made in coordination with Lawrence Berkeley Laboratory, University of California and Atomic Energy of Canada Limited (1) as a contribution to international cooperation on research into radioactive nuclear waste disposal. The granitic rock specimens, originating from the Stripa mine in Sweden, were supplied by the Lawrence Berkeley Laboratory. At the Stripa mine, in situ thermal tests have been performed to test the thermal stability of the rock mass (2). As it is impossible to predict the thermal behaviour of rocks without a knowledge of their thermophysical properties, measured values of thermal diffusivity and thermal expansion may be used for obtaining a correlation with the in situ results. Therefore, both the thermal diffusivity and thermal expansion of rock specimens from several drill cores were measured in unconstrained conditions in the temperature range of approximately 25° to 500°C.

MATERIALS

The granitic rocks for this study were obtained from extensiometer holes drilled in full-scale and extensiometer drifts in the Stripa mine. The exact position of the boreholes is discussed by Kurfurst et al. (3). Four segments were selected by Lawrence Berkeley Laboratory from the following drill cores: E29, E14 and E13. Sample E29 was located 3.15 m into the borehole. The position of sample E14 was at 8.9 m. Two samples were taken from borehole E13, one at 7.5 m and the other at 9.0 m. For purposes of differentiation, specimens E13 are referred to as E13(7.5) and E13(9.0).

The results of a petrographic analysis by Soles (4) of the drill core specimens, E29, E14, E13(9.0) and E13(7.5), are given in Table 1. The position and approximate orientation of the thermal diffusivity specimens are shown in Figure 1. Because the measuring method requires the 2.54 cm diameter specimen column to be 5 cm long, a set of two cylindrical specimens were prepared from each drill core with the exception of drill core E13(7.5). Because of shears and fractions in core E13(7.5) two sets of specimens were prepared: one set (D1) contained only random and relatively small fractures whereas the other set (D2) contained the chlorite-filled fractures. The planes of the fractures were approximately perpendicular to the axes of the cylindrical specimens D2.

The cylindrical thermal diffusivity specimens were 2.54 cm in diameter and 2.54 cm high. The diameter of each cylinder was ground to a tolerance of ±0.0025 cm, with ends lapped plane and parallel. For each pair, one of the cylinders was provided with two 0.75 mm diameter thermocouple holes, about 1.8 cm deep. The thermocouple holes were drilled parallel to the cylinder's axis, one in the centre and the other near the cylindrical surface. The distance between the holes was 1.15 cm.

Figure 1 also shows the approximate orientations and positions from which the thermal expansion specimens were obtained in sample E13(7.5). In this case the thermal expansion specimens were taken from four positions so as to include portions of the rock with chlorite-filled fractures as well as those containing only smaller, random fractures. Because samples E13(9.0), E14 and E29 had no visible large cracks or deformations, specific locations were not designated for extraction of the specimens. The specimens were cut in the form of a rectangular bar, 51 mm long and 8 mm in cross-section.

In addition to indicating the positions of thermal diffusivity and expansion specimens, Figure 1 shows the approximate positions where petrographic specimens were located.

Table 1 - Modal analysis of four drill core segments from the Stripa mine

Mineral	E29		E14		E13(9.0)		E13(7.5)	
	%	Gr. Size mm	%	Gr. Size mm	%	Gr. Size mm	%	Gr. Size mm
Quartz	24.3	0.1-1.5	31.7	0.1-1.5	31.4	0.1-1.5	25.5	0.1-1.5
K-Feldspar	40.6	0.2-2.5	32.9	0.2-1.5	23.7	0.2-2.0	33.7	0.1-2.0
Plagioclase (An15)	24.0	0.2-1.5	25.4	0.2-3.0	38.6	0.2-2.5	26.4	0.1-1.5
Muscovite	5.3	0.2-2.5	1.2	0.3-3.0	1.6	0.2-3.0	3.2	0.2-2.0
Chorite-Biotite	5.7	0.1-1.5	7.6	0.1-1.0	2.5	0.2-3.0	5.0	0.1-1.0
Calcite	-	-	-	-	1.2	0.3	-	-
Epidote	-	-	-	-	0.1	0.1	0.7	0.1
Opaques (Mag., Py)	-	-	1.1	0.3	0.2	0.2	2.5	0.2
Mylonite	-	-	-	-	0.5	1.0	1.0	1.0

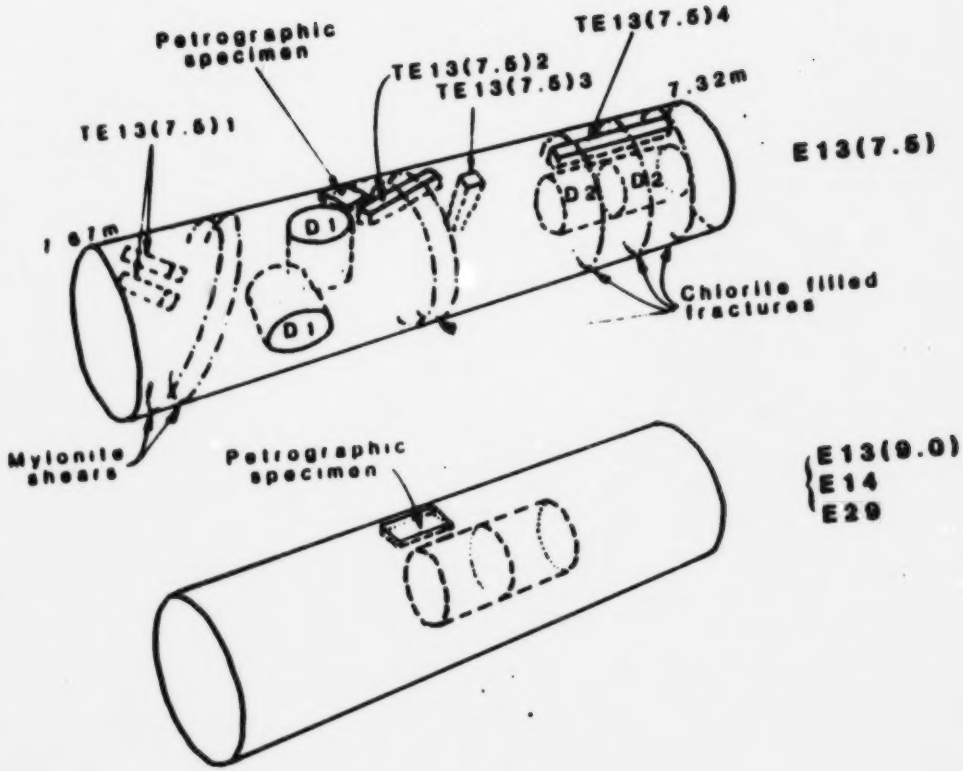

Figure 1. Schematic of positions and orientations of thermal diffusivity and thermal expansion specimens in Stripa drill cores. Thermal diffusivity specimen E13(7.5) D2 and thermal expansion specimens TE13(7.5) 2 and 4 incorporated the chlorite-filled fractures. All other specimens contained only randomly oriented fractures.

THE METHOD OF MEASUREMENT

Most rocks are sensitive to higher temperatures as well as to sudden temperature changes. To measure thermal diffusivity, however, heat pulses must be caused to flow through the specimen. For example, in the laser flash method (5), the surface temperature of the specimen is raised by several hundred degrees (Celsius) in just a few microseconds. To avoid such severe conditions of measurement, a thermal diffusivity apparatus was devised for use on materials both heat-sensitive and relatively coarse grained. In this apparatus, described elsewhere in detail (6,7), heat pulses are generated either in periodic or transient form on the surface of a cylindrical specimen. Their progress is measured from a point near the surface to the centre of the cylinder. For these measurements the periodic method was used. In this case a sinusoidal type heat wave is generated at the surface. The temperature waves are recorded from the two measuring points after the steady state has been attained at a given temperature level. Thermal diffusivity is obtained from the length of the temperature wave, the time required for the wave to traverse the distance from the near-the-surface measuring point to the centre, and the geometry of the specimen. The length of the sinusoidal heat wave was 60 seconds and the temperature oscillation was approximately ± 1°C. Such small and slow temperature variations were not found to be injurious to any rock specimens of the size used in these measurements.

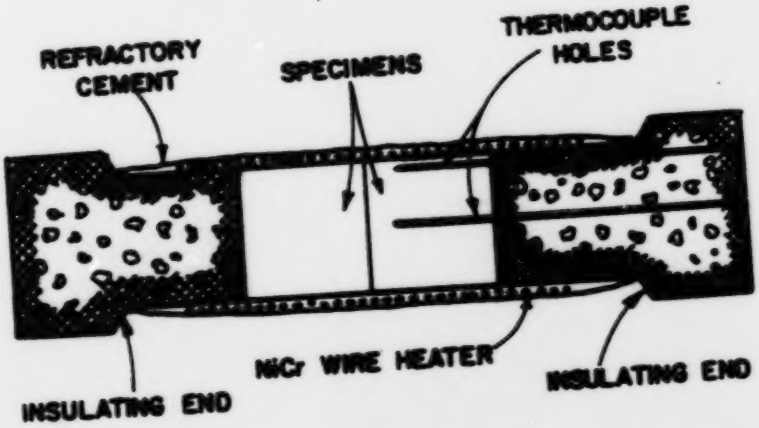

Figure 2. Sample assembly for measurement of thermal diffusivity of rocks

In the experimental configuration the cylindrical sample column shown diagramatically in Figure 2, was composed of two identical rock specimens, each 2.54 cm in diameter and 2.54 cm long, with cylindrical insulators at each end to prevent axial heat losses. Two 0.75-mm thermocouple holes extended through one insulator and approximately 1.8 cm into the first sample. Temperatures were measured with 0.5 mm diameter stainless-steel-shielded chromel-alumel thermocouples. The heat pulses were generated by a B&S 26-gauge nichrome wire heater wound directly on the surface of the cylindrical specimens. All measurements were made in air.

A commercial diliatometer (Industrial Engineering Instrument Company, Allentown, Pa., U.S.A.) employing fused-quartz media was used for thermal expansion measurements. The vertical tube-type furnace is closed at the lower end up to the bottom of the central zone of uniform temperature. This plug supports a fused-quartz tube (22 mm OD and 500 mm long) sealed at the bottom end with a fused-quartz plate. The rock specimen rests on this plate and, in turn, supports a hollow fused-quartz rod, which transmits the elongation of the specimen to a sensitive Ames dial gauge fixed to the external quartz tube. No corrections were applied to compensate for the expansion of the quartz tube as it was considered to be insignificant. A thermocouple was used to measure the temperature at mid-length of the rock specimen. The temperature was increased at approximately 10°C/min.

RESULTS AND DISCUSSION

Thermal diffusivity results are shown in Figures 3 and 4. The curves were fitted to the data by the least squares method. Each curve represents some 11 to 15 thermal diffusivity measurements. They are expressed by a polynomial of the second degree:

$$\alpha = a_1 + a_2 t + a_3 t^2$$

where α is the thermal diffusivity in cm^2/sec and t is the temperature in °C. The equation is valid for the temperature range of 25° to 500°C. The coefficients a_1, a_2 and a_3, as well as the standard and average deviations are given in Table 2.

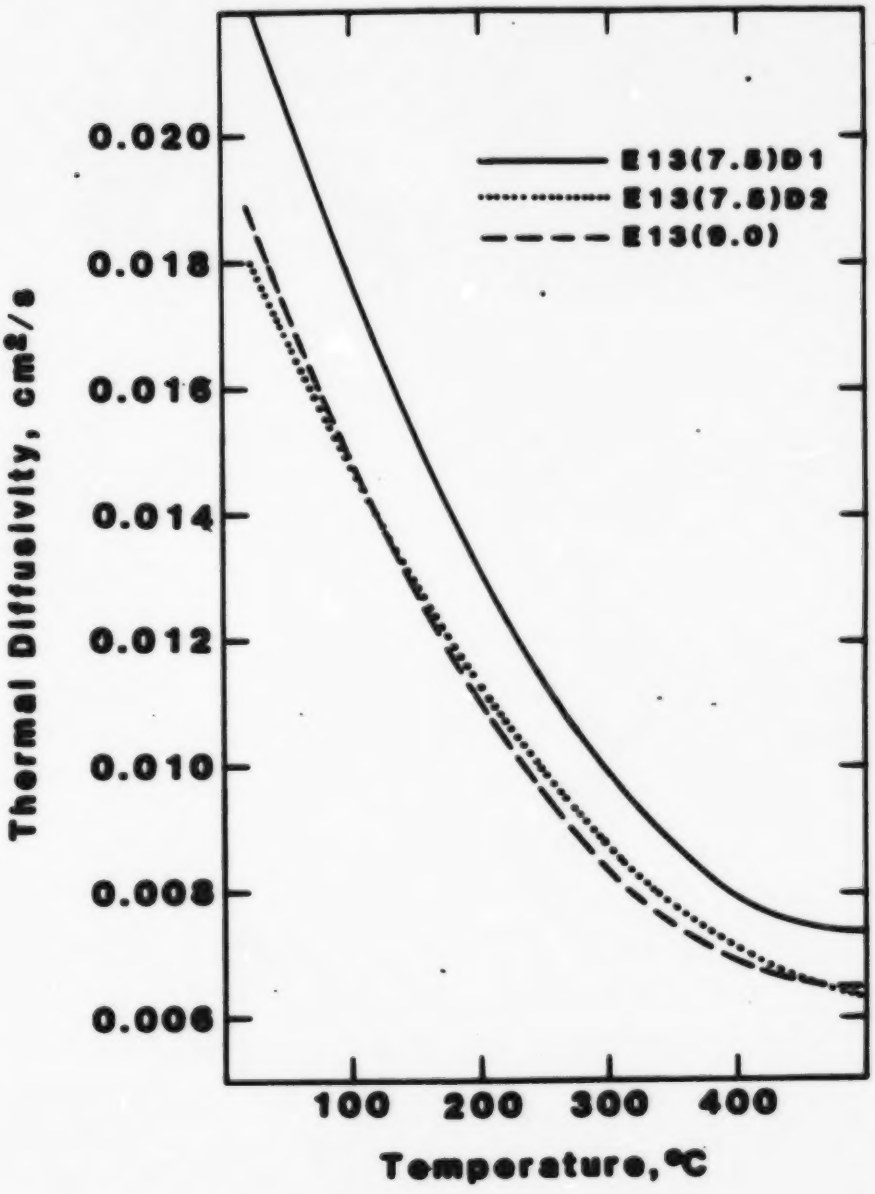

Figure 3. Thermal diffusivity as a function of temperature of Stripa rock specimens from drill cores E13(7.5) and E13(9.0).

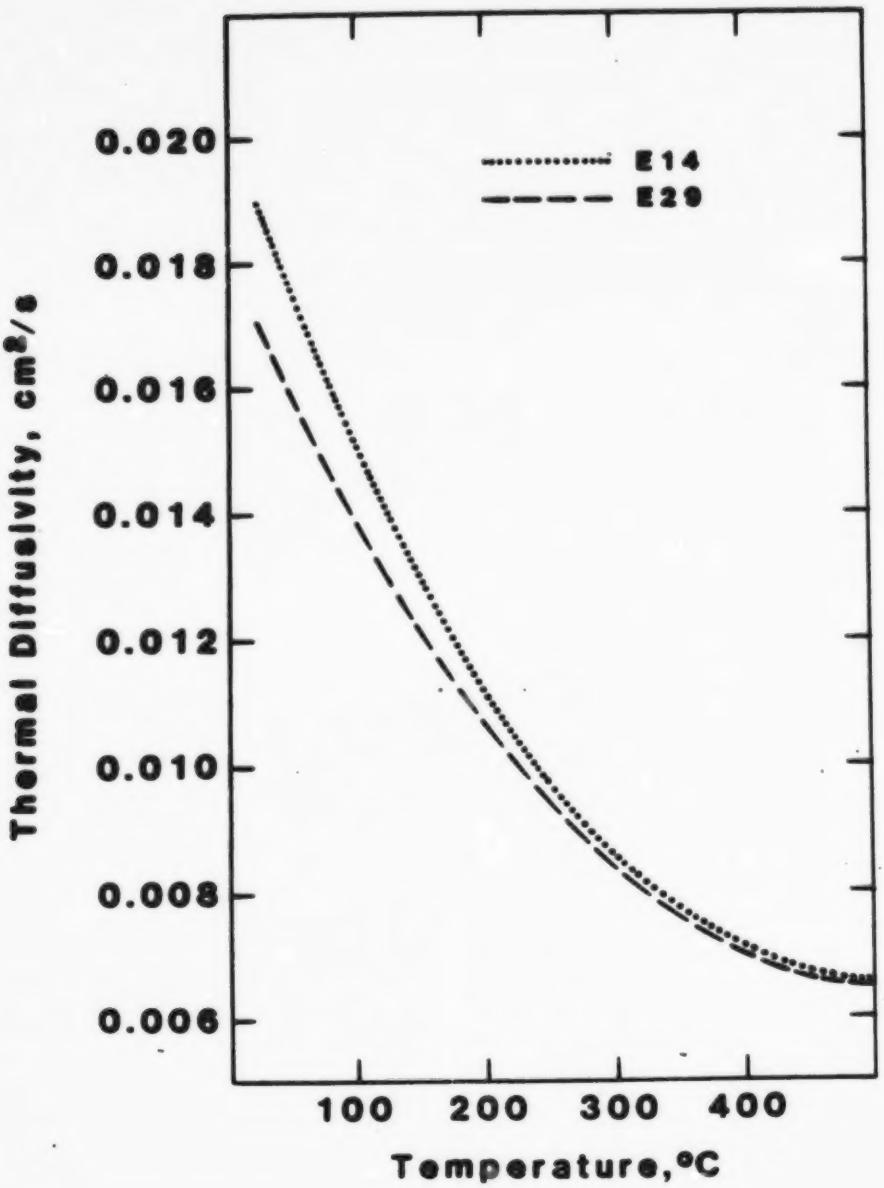

Figure 4. Thermal diffusivity as a function of temperature of Stripa rock specimens from drill core E14 and E29.

Table 2 - Values of constants and standard and average deviations for the polynomial equation representing thermal diffusivity of Stripa drill core rocks

Rock	Coefficients			Deviations %	
	$a_1 \times 10^2$	$a_2 \times 10^5$	$a_3 \times 10^8$	Standard	Average
E13(7.5)D1	1.905	-4.769	4.464	1.1	1.9
E13(7.5)D2	2.010	-5.682	5.978	2.0	2.5
E13(9.0)	2.374	-6.665	6.815	1.6	1.6
E14	2.047	-5.873	6.273	1.5	2.1
E29	1.823	-4.702	4.734	0.7	1.4

It can be seen from Figures 3 and 4 that, with the exception of specimen E13(9.0), the thermal diffusivities of Stripa rock specimens do not differ significantly from each other. At lower temperature the thermal diffusivity of E13(9.0) is about 20% higher than that of E13(7.5)D1 and E13(7.5)D2. This difference decreases to about 15% at higher temperatures.

The thermal transport properties of quartz are appreciably greater than those of the other major mineral components, and the higher thermal diffusivity of E13(9.0) should therefore be a reflection of the higher quartz content of this specimen. However, that does not seem to be the case with specimen E14, whose quartz content is as high as that of E13(9.0). The thermal diffusivity of E14 closely approximates the diffusivities of E13(7.5)D1 and D2 and E29. Furthermore, comparing specimens E13(7.5)D1 and D2, one observes no difference in their thermal diffusivities. Because E13(7.5)D2 is a layered specimen with chlorite-filled fractures oriented parallel to the heat flow, its thermal diffusivity should be higher than that of E13(7.5)D1 (which contains only random fractures). Clearly, in the case of these highly fractured rocks, factors such as the tightness of the intergranular bonds, fracture distribution and fracture healing exert greater influence on thermal diffusivity then the mineralogical composition.

Their highly fractured nature is probably also responsible for the large dependence of thermal diffusivity on temperature. The room temperature thermal diffusivity values of the Stripa specimens are very high. Unfortunately, with increasing temperature, possibly because of

fracture opening, these values decrease rapidly. For example the thermal diffusivity of specimen E13(9.0) decreases by approximately 25% between 25° and 125°C. Such a rapid decrease would cause steeper thermal gradients, - an undesirable feature from the point of view of a rock repository for the heat-generating nuclear waste.

The results of thermal expansion measurements for the temperature range of 25° to 500°C are shown in Figures 5 and 6. The results from the four specimens from sample E13(7.5) are presented in Figure 5. As can be seen, the difference in expansion between these specimens is very small. Because of the structured nature of TE13(7.5)-2 and -4, one could expect that the thermal expansion of these specimens would be larger than that of TE13(7.5)-1 and -2. However, because of the small apparent differences only a trend to that effect can be identified.

The thermal expansion of specimens TE13(9.0), TE14 and TE29 were found to be essentially the same and are represented by a single line in Figure 6. The thermal expansion of this group of rocks approximates closely the values obtained for the E13(7.5) group.

All curves are continuous, indicating that in this temperature range none of the specimens undergo sudden structural changes. It is interesting to note that in these rock specimens thermal expansion becomes measurable only after a temperature increase of about 50°C. In part, this apparent lack of expansion at low temperature may have been caused by the difference in the heat capacities between the rock specimen and the thermocouple. The thermocouple, having much lower heat capacity, would react faster to the temperature change. On the other hand, the initial lack of expansion could have been caused by intrinsic properties of the rock.

Page and Heard (8) and Heard and Page (9) have on several occasions observed an anomaly in the thermal expansion of certain igneous rocks under pressure. They found that the thermal expansion of rocks such as Westerly and Stripa granites increased more slowly at temperatures below 100-150°C than the sum of values for their mineral components only (i.e. for a rock without pores and cracks). In fact, the thermal expansion of Stripa rocks was found to be slightly negative below 100°C. Mirkovich et al. (10) measured thermal diffusivity of that particular Stripa granite specimen and found that under high pressure (200 MPa) the thermal diffusivity actually increased with increasing temperature from 25° to 60°C. The authors observing this anomaly rationalized that a portion of thermal expansion

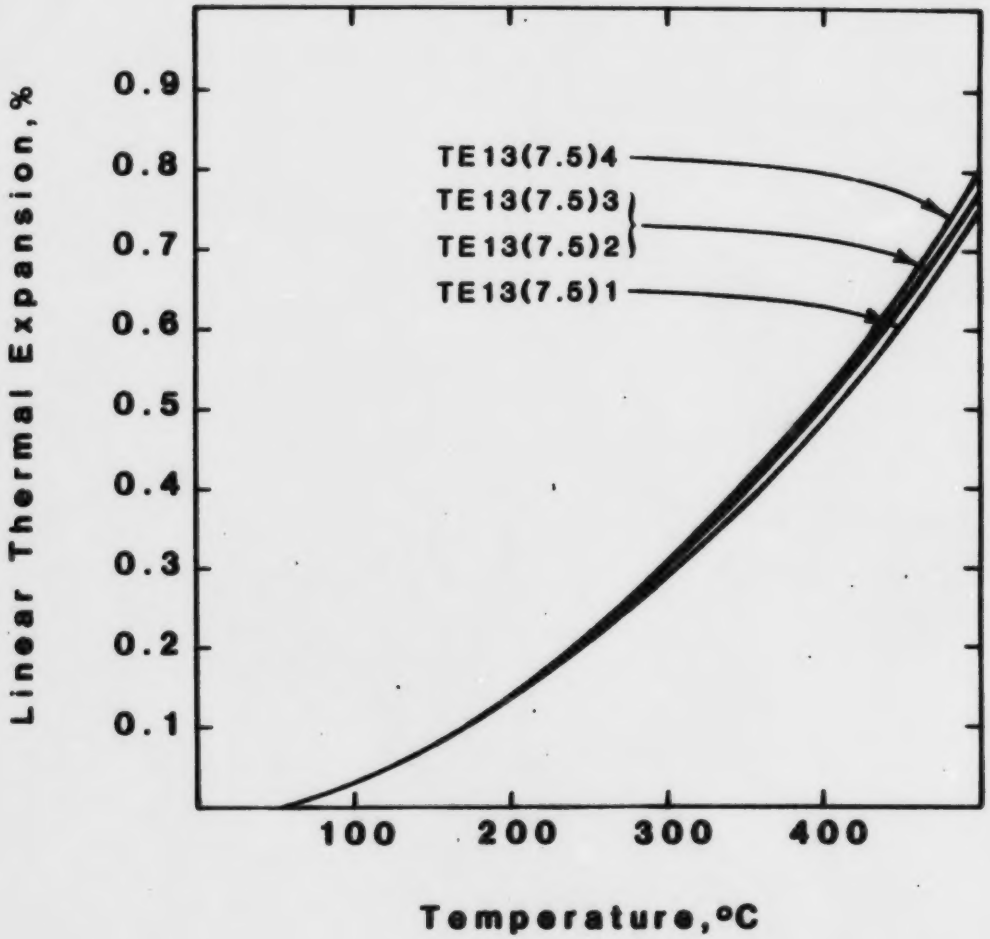

Figure 5. Linear thermal expansion of Stripa rock specimens from drill core E13(7.5).

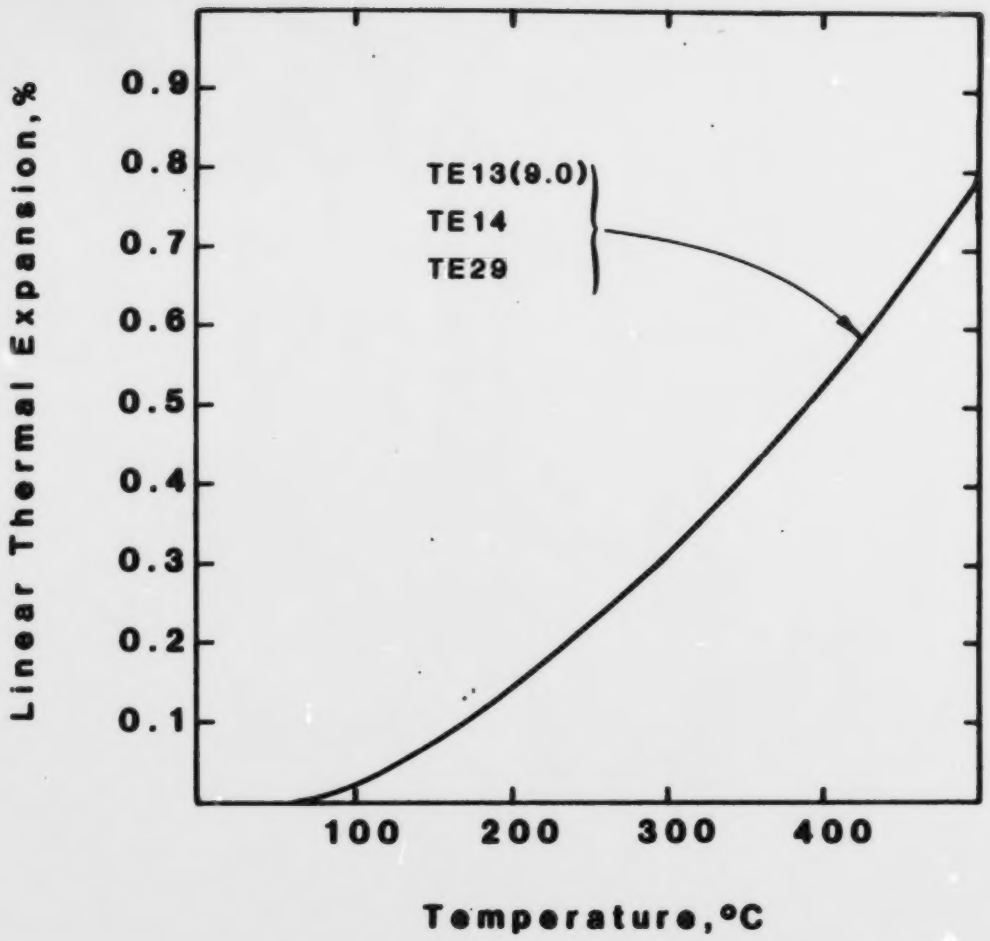

Figure 6. Linear thermal expansion of Stripa rock specimens from drill cores E13(9.0), E14 and E29. The difference between the expansions of these specimens is so small that the results can be presented by the single curve.

at the low temperatures was accommodated internally, i.e. by a decrease of the pore space.

In the present measurements, which were made at atmospheric pressure, thermal diffusivity of all specimen decreases monotonically with increasing temperature and the transport properties do not show an inflection at the lower temperature. Nevertheless, the initial delay in the measured expansion may have been caused by internal expansion, similar to the ones observed by the authors above. Such a phenomenon, if it does occur, would be beneficial from the point of view of nuclear waste storage: kept at sufficiently low temperature, the permeability of the rock mass surrrounding the repository may actualy decrease and thus make the repository less accessible to underground water currents.

Heated rock surfaces tend to spall. An empirical equation, obtained in a previous study (11) was used to estimate the spalling tendency of Stripa rocks. The equation,

$$R = 21.3\alpha E - 1.75 \times 10^{-2}$$

where R is the piercing rate (cm/s), α is the thermal diffusivity (cm^2/s) and E is per cent elongation, was found to be valid for predicting high-temperature thermal piercing rates of rocks. The values for α are taken at 200°C and that of E at 500°C. Although the validity of the above relation is likely to be limited to the conditions of piercing with high-temperature jet flames impinging on a relatively small surface, it may also serve, on a comparative basis, as an indicator for spalling of rocks under different heating conditions. The piercing rates calculated from the above equation for Stripa rock specimens are given in Table 3.

Table 3 - Piercing rates for Stripa rocks when subjected to a high surface heat transfer

Specimen	α [cm^2/s]	E[%]	R[cm/s]
E13(7.5)D1	0.0113	0.77	0.17
E13(7.5)D2	0.0111	0.77	0.16
E13(9.0)	0.0131	0.80	0.21
E14	0.0107	0.79	0.16
E29	0.0112	0.79	0.17

Data previously obtained (12,13,14) for rock studies in this program have shown that the piercing rates can range between 0.05 and 0.17 cm/s. In the jet-piercing investigation (15) piercing rates of 0.20–0.25 cm/s were considered to be good to excellent as continuous piercing could be maintained. Assuming that the rates shown in Table 3 could serve as an indicator for spalling of the Stripa rocks under conditions that might exist in an underground repository containing heat-generating radioactive nuclear waste, then the spalling probability for all rocks would be high. The rock mass represented by specimen E13(9.0) would spall extensively. Generally, the thermomechanical stability of a cavern excavated in this rock mass would be quite low.

CONCLUSIONS

The principal conclusions of this study are as follows:

1. Thermal diffusivity of Stripa rocks is high at room temperature, but it decreases rapidly with increasing temperature.

2. The linear thermal expansion is relatively high. The curves show continuity in the 25°–500°C temperature range. There is some evidence that internal expansion occurs between 25° and 75°C.

3. The projected spalling rates for Stripa rocks are high, indicating that the thermomechanical stability of the surfaces of a nuclear waste repository would be low.

ACKNOWLEDGEMENTS

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